AD-A234 483

(2)

TECHNICAL REPORT BRL-TR-3226

BRL

SURVIVABLE TIRE SYSTEM (STS) TEST ANALYSIS: STAGE 1 SURVIVABILITY

BARRY A. BODT
JAMES E. SCHALL, JR.

APRIL 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

UNCLASSIFIED

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1991

3. REPORT TYPE AND DATES COVERED
Final, Mar 1990 - Jan 1991

4. TITLE AND SUBTITLE
Survivable Tire System (STS) Test Analysis: Stage 1 Survivability

5. FUNDING NUMBERS
PR: 1L162618AH80

6. AUTHOR(S)
Barry A. Bodt and James E. Schall, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
BRL-TR-3226

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The standard survivable tire system (STS) for the High Mobility Multi-Purpose Wheeled Vehicle (HMMWV) was tested with respect to survivability at the Nevada Automotive Test Center (NATC) near Carson City, NV. This test was the first of two stages in the technical phase of a program intended to result in an improved survivable tire system. The purposes of Stage 1 were to establish a baseline of performance for the standard system, to explore test conditions which significantly influence system survivability, to make recommendations for the conduct of Stage 2, and to pilot testing techniques developed by the Ballistic Research Laboratory (BRL). This document details the extent to which the first three of the stated purposes were satisfied; the success of the last is implicit in the high quality of the data produced.

14. SUBJECT TERMS
Survivable Tire Systems; Fractional Factorial Designs; Screening Tests; High Mobility Multi-Purpose Wheeled Vehicle; Analysis of Variance; Survivability

15. NUMBER OF PAGES
34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

LIST OF TABLES

INTENTIONALLY LEFT BLANK.

ACKNOWLEDGMENTS

The authors express their thanks to several individuals who contributed to this project. Mr. Tom Martindale and Mr. Rick Kane of the Ballistic Research Laboratory (BRL) conducted the firing in which the tires were degraded. Mr. Carroll Moore of Nevada Automotive Test Center (NATC) oversaw the trials and served as the final authority in determining when the tire system had failed in accordance with the failure criteria. Ms. Frances Gillam of Nomura Enterprise Inc. (NEI) prepared the document, and Mr. Eric Edwards of NEI provided an editorial review. Finally, Dr. Ken Unruh of Army Materiel Systems Analysis Activity (AMSAA) and Mr. Dave Webb of BRL reviewed this report for its technical content.

INTENTIONALLY LEFT BLANK.

1. INTRODUCTION

1.1 Recent History. A survivable tire system (STS) was tested during January and February of 1990 in the first of two test stages defining the Ballistic Research Laboratory's (BRL) technical approach to evaluating STS survivability. Under the direction of the Vulnerability and Lethality Division (VLD) of the BRL, the Nevada Automotive Test Center (NATC) conducted the testing at its facility near Carson City, NV. Analysis of the test results was performed by the Probability and Statistics Branch (PSB) of the System Engineering and Concepts Analysis Division (SECAD) of the BRL.

The need for the test stems as much from durability requirements as it does survivability. The survivability aspect of an STS refers to its capability to support vehicle mobility after some tires have been degraded in the field by, for example, ammunition, shell fragments, and battlefield debris. The standard STS (the subject of Stage 1) for the High Mobility Multi-Purpose Wheeled Vehicle (HMMWV) consists primarily of a radial tire and a magnesium run-flat device onto which the tire collapses after losing pressure. The standard STS is believed to meet the survivability requirement outlined in the NATO/FINABEL Standard, dated 5 January 1984, but fails the durability requirement because in normal operation the run-flat device causes excessive wear to the interior of the tire. The program, of which this test is a part, focuses on the development of new STS technologies likely to improve the durability of the STS with no reduction of, and preferably with an enhancement to, survivability. Survivability, the more important requirement of the two, will be used to screen candidates promising to address the durability issue—the survivability requirement must be met first. In Stage 1 a baseline performance is established for survivability.

An overview of the program will help place this test, and the BRL's involvement, in perspective. In 1985 the Tank Automotive Command (TACOM) established a tire task force which oversees the program. A two-phase approach (operational and technical) was adopted. In 1987 the Combat Development Experimentation Center (CDEC) and the Waterways Experimentation Station (WES) released reports detailing different aspects of the operational phase conducted at Fort Lewis, WA. Combined results included performance rankings of the systems tested, suggestions for STS modifications, and recommendations for pertinent data to be collected in subsequent tests. In addition, problems with wet conditions during the

Fort Lewis test contributed to the selection of the more arid NATC as the location for the technical phase of testing.

In 1990 the BRL released a report describing the test strategy for the technical test phase. TACOM had enlisted the support of BRL to devise means for, among others, simulating fragment damage, damaging tire systems while in motion and under load, determining the influence of several test condition factors, and assessing the performances of five candidate systems relative to each other and the standard system. To meet the TACOM requests, the technical phase was divided into two stages. Stage 1 focuses on the current system. Stage 2 focuses on the candidate systems. A thorough description and supporting rationale for the test strategy is given in BRL-TR-3111 (Bodt, Schall, and Snapp 1990).

1.2 Stage 1 Objectives. The principal objectives of Stage 1 were to measure the baseline performance of the standard HMMWV STS for comparison with several prototype systems and to refine the test strategy for implementation in Stage 2 where those comparisons would be made. Refinements in the test procedure were anticipated to be necessary because TACOM had requested a number of test conditions be screened and not all were likely to influence the measured response. Other refinements would possibly be required based on the initial testing experiences with a new BRL test stand, with fragment simulation, and with driver instructions for traversing the difficult test course. Only the standard STS was used in Stage 1 because it was considered wasteful to address procedural concerns using the limited-in-number and more expensive tire resources from the candidate systems.

1.3 Purposes and Organization. The purposes of this document are to detail the analysis of Stage 1 testing and to support the decisions made regarding the conduct of Stage 2.

The remainder of the report is partitioned as follows. Section 2 gives an overview of the experiment strategy implemented in Stage 1. Section 3 reports the statistical analysis of the test results. Section 4 discusses recommendations for the second stage of testing, and Section 5 summarizes the accomplishments of Stage 1.

2. EXPERIMENT SUMMARY

The purpose of this section is to provide a brief overview of the Stage 1 experiment design. Testing had to conform with requirements outlined in the NATO/FINABEL standard, and the complete test description is contained in BRL-TR-3111. The salient features described in that report are repeated here for the reader's convenience. This section, and the parallel-structured Section 3, discusses the speed profile and screening portions of the Stage 1 test.

2.1 Speed Profile Test. Failure criteria for an STS are partially dependent on normal operating performance—that is, STS performance in a nondegraded mode. The relevant criterion states that an STS has failed if mobility can only be safely supported at 50% or less of the normal operating speed. This is termed the 50% Rule. What is considered normal may change with experimental factors such as driver, driving team, pressure, or terrain. Normal operating speeds for the standard STS, under certain experimental factors, were measured in a speed profile test.

The speed profile test was conducted under the same experimental conditions to be used in the subsequent screening test. Two driving teams, with two drivers each, traveled four laps of the test course, recording times on each segment of the course as they went. Low tire pressure (22 psi) runs were made in four of the eight laps and high tire pressure (30 psi) runs were made in the remaining four laps, with each driver experiencing each pressure for one full lap. (See Table 1.) The course was 30 mi long and was comprised, in 21 course segments, of cross-country, secondary road, and primary road in distances of 12 mi, 9 mi, and 9 mi, respectively. Tire performance evaluation sheets were completed by each driver at the conclusion of each lap.

Normal operating performance was to be modeled based on the gathered data. The influence on speed of driver, team, pressure, and terrain was to be studied graphically and through applications of the general linear model, a tool in statistics. The result was to be a model of baseline performance with as many different speed values for different experimental conditions as were warranted based on the analysis. The evaluation sheet data were to be retained for comparison with nondegraded runs of candidate tires in Stage 2.

Table 1. Speed Profile Test Design

Test Sequence	Team	Vehicle	Lap	Tire Pressure, psi	Driver No.	Data Collector
1	1	1	1	30	1	2
2	1	1	2	30	2	1
3	1	1	3	22	1	2
4	1	1	4	22	2	1
5	2	2	1	30	1	2
6	2	2	2	30	2	1
7	2	2	3	22	1	2
8	2	2	4	22	2	1

2.2 Screening Test. A fractional factorial design was used as the framework for a screening test to satisfy the objectives of Section 1.2. The response for the design was the number of miles until STS failure after degradation. Failure was initially defined as occurring in one of two ways. One, the 50% Rule, is defined in Section 2.1. Run-flat failure occurred when the run-flat device broke up in some fashion or when the STS would no longer support vehicle progress. However, in early trials testing occasionally had to be stopped for other reasons, loosely termed "vehicle failure." Vehicle failure occurred when the vehicle became inoperable as a direct result of damage or when a situation arose creating obvious risk for substantial vehicle damage. The decision was made to consider such vehicle failures a consequence of the tire system's performance. For example, one trial was stopped when pieces of the run-flat damaged the right-rear half shaft. Failure determinations were made by the Test Director at NATC.

The design was run as a 1/2 replicate of a 4×2^4 factorial, consisting of one factor at four levels and four factors at two levels. (See Table 2.) The four-level factor, threat, includes each method of tire degradation—two by 7.62-mm rounds, one by a 3-g (gram) fragment simulator, and one by a 10-g fragment simulator. All methods called for shooting into the sidewall five times and into the tread two times. All sidewall shots were perpendicular to the direction of the tire except for one 7.62-mm method where the angle of entry was 45°. Two tire pressures, 22 psi and 30 psi, were tested. Two states of motion were also tested, static (tires at rest) and dynamic (tires rolling at 35 MPH). The BRL test stand allowed dynamic shots to be made with the tires rolling and under load but with the vehicle mounted on the stand. The factor levels of tire position were drive and steering. Two driving teams made up the levels of the final factor included in the factorial design.

Table 2. Screening Test Design

Test Sequence	Threat	Team	Tire Pressure, psi	Tire Position	Tire Motion
16	3 g	1	22	drive	static
2	3 g	1	22	steering	dynamic
32	3 g	1	30	drive	dynamic
4	3 g	1	30	steering	static
1	3 g	2	22	drive	dynamic
27	3 g	2	22	steering	static
19	3 g	2	30	drive	static
21	3 g	2	30	steering	dynamic
18	10 g	1	22	drive	dynamic
6	10 g	1	22	steering	static
26	10 g	1	30	drive	static
36	10 g	1	30	steering	dynamic
33	10 g	2	22	drive	static
9	10 g	2	22	steering	dynamic
5	10 g	2	30	drive	dynamic
7	10 g	2	30	steering	static
24	7.62 mm/45°	1	22	drive	dynamic
34	7.62 mm/45°	1	22	steering	static
22	7.62 mm/45°	1	30	drive	static
28	7.62 mm/45°	1	30	steering	dynamic
31	7.62 mm/45°	2	22	drive	static
17	7.62 mm/45°	2	22	steering	dynamic
11	7.62 mm/45°	2	30	drive	dynamic
3	7.62 mm/45°	2	30	steering	static
14	7.62 mm/90°	1	22	drive	static
12	7.62 mm/90°	1	22	steering	dynamic
30	7.62 mm/90°	1	30	drive	dynamic
8	7.62 mm/90°	1	30	steering	static
13	7.62 mm/90°	2	22	drive	dynamic
25	7.62 mm/90°	2	22	steering	static
23	7.62 mm/90°	2	30	drive	static
35	7.62 mm/90°	2	30	steering	dynamic
20	*3 g*	*1*	*22*	*2-tire*	*dynamic*
15	*3 g*	*2*	*30*	*2-tire*	*dynamic*
10	*7.62 mm/90°*	*1*	*22*	*2-tire*	*dynamic*
29	*7.62 mm/90°*	*2*	*30*	*2-tire*	*dynamic*

Other factors which were expected to affect the response were built into the design but not as part of the factorial construct. Terrain types were included by incorporating them in the test course in percentages consistent with the HMMWV's mission profile. Two different HMMWVs were used. Their influence was not of great interest (vehicle maintenance was not the focus here) so we allowed their effect to be confounded (i.e., made statistically indistinguishable) with driving team. For either driving team or vehicle, the intent was to partition out its variability so it would not be included in the error term for the planned analysis of variance. The load for the vehicle was set at its maximum of 7,900 lb. The distribution of that load was determined by TACOM and NATC. The effect on system failure brought about by two tires being damaged instead of one was also measured. Four runs (denoted by italicized type in Table 2) were conducted with both the right side drive and steering tires degraded. These runs were imbedded in the factorial design in a random manner. Their comparison with single-degraded-tire runs was necessary because the vehicle requirements are stated in terms of performance when at most two tires are damaged; however, to have given the question more emphasis than this would not have been possible with available resources.

3. TEST ANALYSIS

3.1 Speed Profile Test. The principal analytical result of the speed profile test was to be a characterization of normal operating performance that could be used as a reference in the determination of the 50% Rule. The characterization chosen is, for each course segment, the average speed recorded over the eight runs. No complex functional description is required; moreover, the factors team, driver, and pressure do not sufficiently influence the data to warrant inclusion as model parameters. Supporting discussion follows.

Data from the speed profile test are depicted graphically in Figures 1 and 2. In Figure 1, the speeds traveled over each of the 21 course segments were computed based on the times recorded at checkpoints 2–22. All eight combinations of team, driver, and pressure are shown. Figure 2 contains the maximum and minimum speeds recorded for each course segment. The type of terrain, cross-country, secondary, or primary (denoted x, s, or p, respectively) is listed above each maximum speed recorded. The average range of the eight speeds recorded for each course segment is 2.4 MPH, and the maximum range is 6.8 MPH, recorded at checkpoint 18. Excluding from consideration the primary terrain, on which the

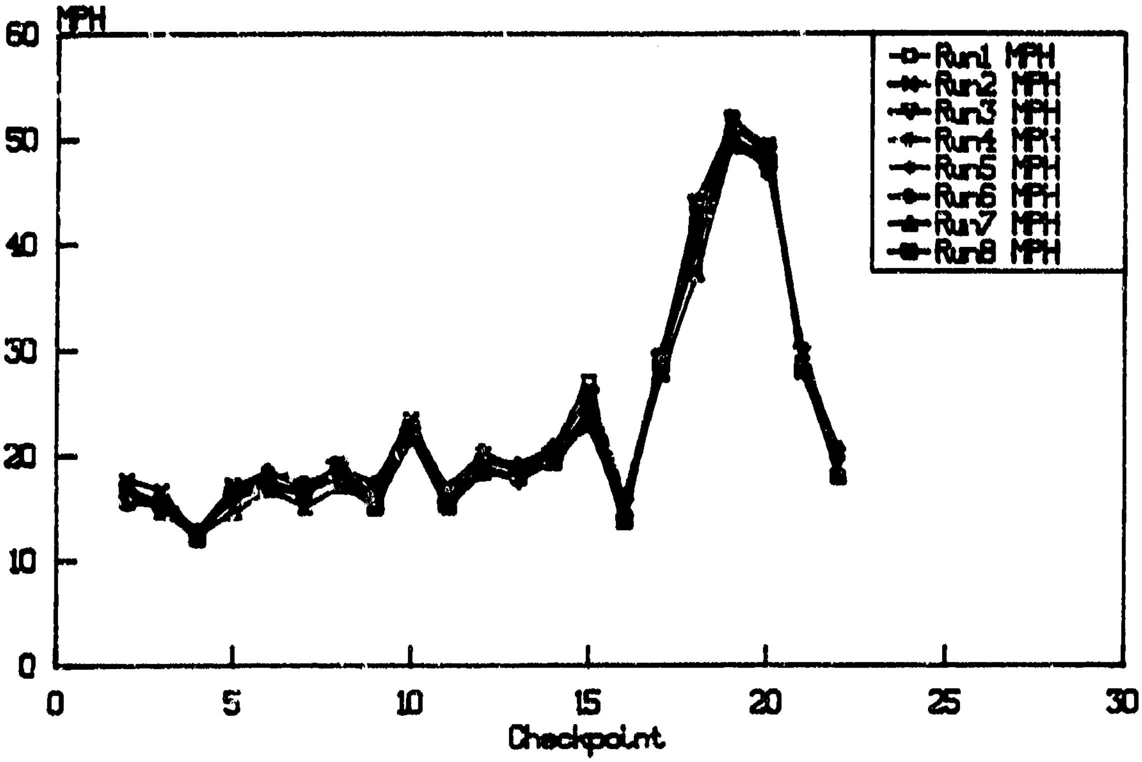

Figure 1. Speed Recorded for Eight Course Profile Runs.

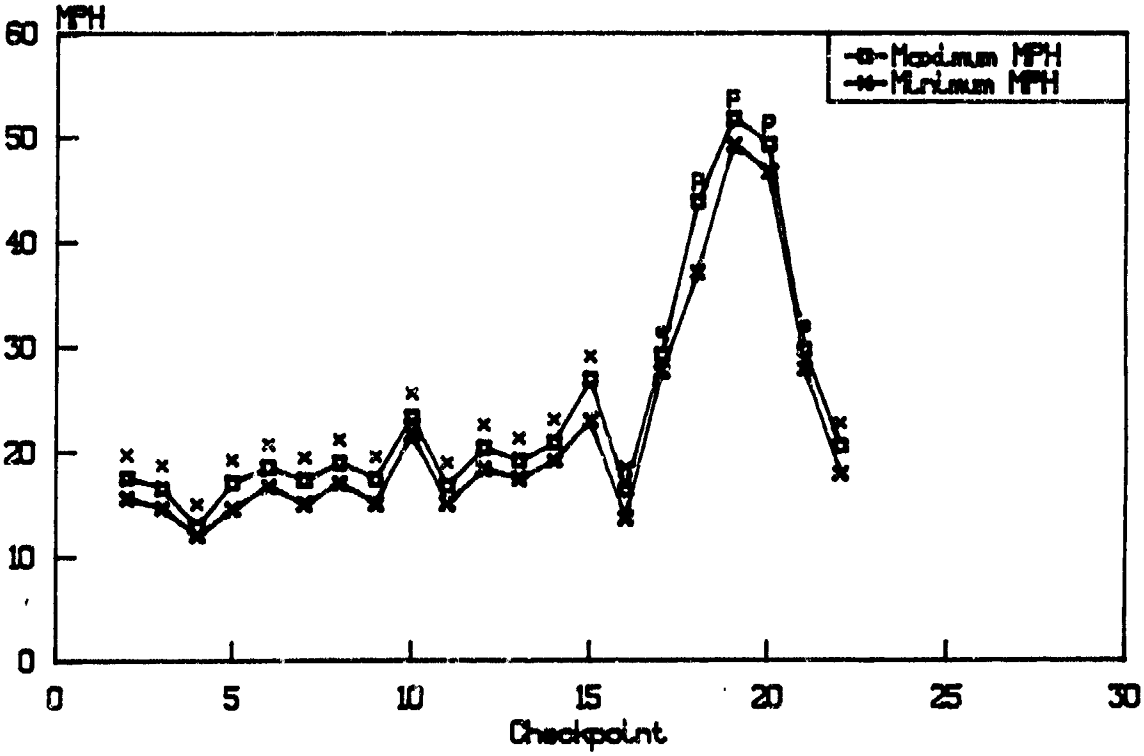

Figure 2. Minimum and Maximum Speeds Recorded for Each Course Segment.

speeds are not representative of the 35-MPH limit later set for the screening test, the average range is 2.1 MPH, and the maximum range is 4.0 MPH, recorded at checkpoint 15. These figures clearly show that terrain, as well as course segments within a terrain type, greatly influences the normal operating speeds while the effects of the other three factors amount to very little.

Table 3 further supports the idea that only terrain is important in determining speed. The tabled values are representative speeds recorded over all course segments of each terrain type and within each team, driver, and pressure combination. These representative speeds were computed as the average speed required to correspond to the total time it took to traverse all segments of a given terrain type. For the statistically literate reader who sees significant main effects in this table other than terrain, we did also; further, as an exercise in exploratory data analysis, we ignored the nonrandomness issue and ran an analysis of variance on the nested design. Depending on what is chosen as the error term, one will find statistically significant pressure and team main effects and pressure by team interaction in addition to terrain; however, given the size of the effect, only terrain has any practical significance for the modeling application.

The normal (average) operating speeds and corresponding 50% level performance for each course segment are given in Figure 3. When operating speeds in the screening test reach or dip below the 50% level performance, the tire system is considered to have failed.

A secondary analytical result was the examination of subjective assessments about the tire made by drivers at the end of each lap. These are discussed in Appendix A in conjunction with assessments made during the screening test.

3.2 Screening Test. Answering questions regarding the importance of test factors in influencing survivability is the main focus of this section. Among the factors threat, team, position, pressure, and motion, only threat, team, and position significantly affect the response--miles until failure after degradation. Position was so important that a single degraded drive tire yielded similar results to the four runs in which two tires were damaged. In the following, details supporting these findings are presented.

Table 3. Average Profile Run Speeds

		Team 1		Team 2	
		Driver 1	Driver 2	Driver 1	Driver 2
Cross-	22 psi	17.0	17.0	16.3	16.4
Country	30 psi	17.0	17.3	16.8	17.2
Secondary	22 psi	29.5	29.0	27.8	28.2
Road	30 psi	29.0	28.5	28.7	28.6
Primary	22 psi	49.3	47.5	46.8	47.5
Road	30 psi	49.3	47.6	47.9	48.7

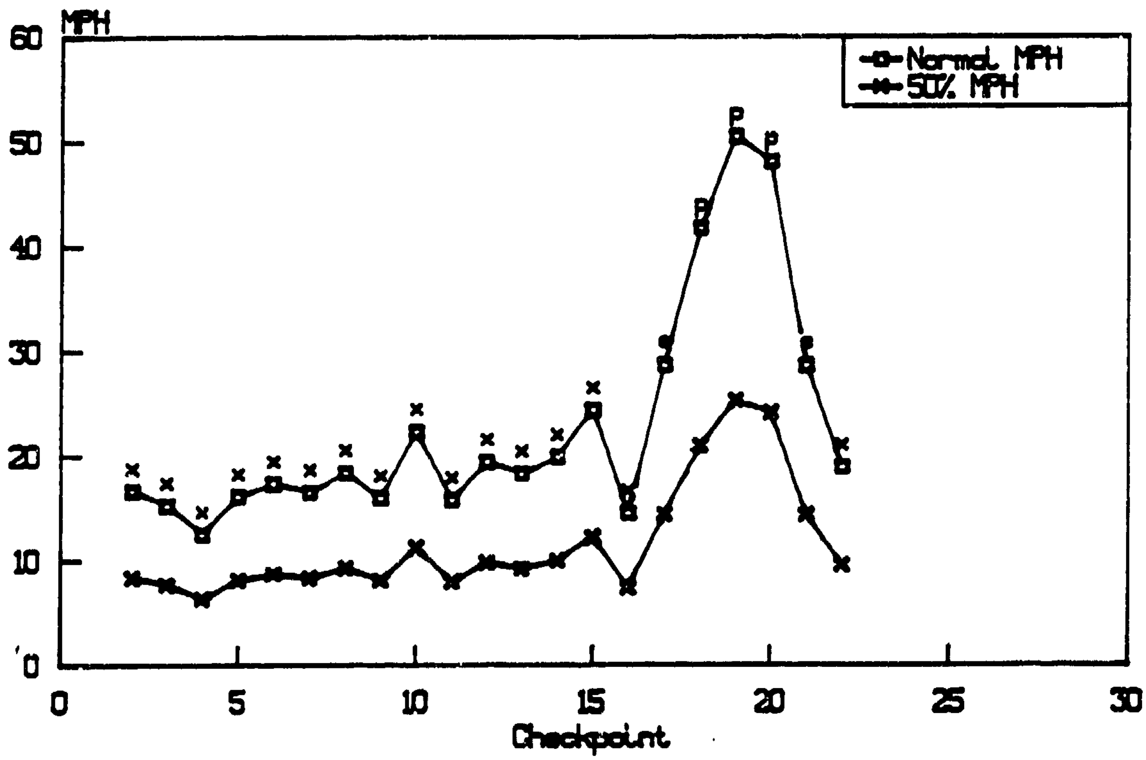

Figure 3. Normal Course Speeds and 50% Performance Speeds.

Data were collected in accordance with BRL-TR-3111. NATC strictly adhered to the randomized (with some restrictions) test sequence, tire rotation schedules, and failure determination guidelines. Firing was performed by BRL gun crews who also implemented the BRL test stand for the dynamic level of the motion factor. The resulting data appear in Table 4. In reference to failure determination, only test number 32 was stopped due to vehicle failure (differential locked). All other test runs were stopped directly because of STS failure. Test number 4 was stopped because of a power steering pump failure only 4 mi into the course and then was restarted after repairs were made. This run preceded the concerns over vehicle damage and the eventual classification of vehicle failure and was allowed to stand as originally reported. An unusually high value of 84.9 mi for test number 28 was flagged as an outlier, but, after discussion with the Test Director at NATC, no justification to discount it as errant could be made. This observation was not excluded from the analysis. Test numbers 3 and 8 were rerun, the former because of excessive speed on the primary road, the latter because of a snow shower.

The statistical analysis performed was of a 1/2 replicate of a 4×2^4 factorial design. In such an analysis, the four-level factor is broken out into two pseudofactors having two levels each, which, when combined with the remaining two-level factors, can be analyzed as a 1/2 replicate of a 2^6 design. The sum of squares associated with the original four-level factor are retrieved as the sum of the main effect and interaction sum of squares attributed to the pseudofactors (Kempthorne 1952). In Table 5, the analysis of variance results are given in terms of the original five-factor design. The table includes the source of the influence on the response, its degrees of freedom (df), sum of squares (SS), mean square (MS), and associated sample F-statistic (F). For explanation of these terms, see Cochran and Cox (1957). The effects found significant at the α=.10 or α=.05 level are denoted by *, or **, respectively. Significance of an effect at the α=.10 level means that if we claim that effect influences the response, we do so with only a probability of .10 of being wrong. In a fractionated design, there is no estimate of error variance. In keeping with accepted methods, higher (second) order interactions were considered not present, and their small measured effects were combined to serve as an estimate of error. One interaction, involving threat, pressure, and position was excluded from the error term because of its unusually large sum of squares relative to the other second-order interactions. The interaction is ignored in the

Table 4. Screening Test Data (Miles)

SCREENING TEST RESPONSES						
Test Sequence	Threat	Team	Tire Pressure, psi	Tire Position	Tire Motion	Miles
1	3 g	2	22	drive	dynamic	20.4
2	3 g	1	22	steering	dynamic	33.7
3	7.62 mm/45°	2	30	steering	static	24.9
4	3 g	1	30	steering	static	50.4
5	10 g	2	30	drive	dynamic	54.9
6	10 g	1	22	steering	static	40.9
7	10 g	2	30	steering	static	24.9
8	7.62 mm/90°	1	30	steering	static	31.3
9	10 g	2	22	steering	dynamic	35.9
10	*7.62 mm/90°*	*1*	*22*	*2-tire*	*dynamic*	30.0
11	7.62 mm/45°	2	30	drive	dynamic	32.9
12	7.62 mm/90°	1	22	steering	dynamic	65.9
13	7.62 mm/90°	2	22	drive	dynamic	20.4
14	7.62 mm/90°	1	22	drive	static	33.7
15	*3 g*	*2*	*30*	*2-tire*	*dynamic*	24.9
16	3 g	1	22	drive	static	46.6
17	7.62 mm/45°	2	22	steering	dynamic	32.9
18	10 g	1	22	drive	dynamic	20.4
19	3 g	2	30	drive	static	31.3
20	*3 g*	*1*	*22*	*2-tire*	*dynamic*	32.9
21	3 g	2	30	steering	dynamic	30.7
22	7.62 mm/45°	1	30	drive	static	30.7
23	7.62 mm/90°	2	30	drive	static	30.7
24	7.62 mm/45°	1	22	drive	dynamic	50.4
25	7.62 mm/90°	2	22	steering	static	54.9
26	10 g	1	30	drive	static	34.6
27	3 g	2	22	steering	static	24.9
28	7.62 mm/45°	1	30	steering	dynamic	84.9
29	*7.62 mm/90°*	*2*	*30*	*2-tire*	*dynamic*	20.4
30	7.62 mm/90°	1	30	drive	dynamic	31.3
31	7.62 mm/45°	2	22	drive	static	32.9
32	3 g	1	30	drive	dynamic	35.0
33	10 g	2	22	drive	static	18.3
34	7.62 mm/45°	1	22	steering	static	54.9
35	7.62 mm/90°	2	30	steering	dynamic	24.9
36	10 g	1	30	steering	dynamic	32.9

Table 5. Analysis of Variance Table for Screening Test

Source	df	SS	MS	F
Threat	3	492.81	164.27	4.67*
Team	1	1,029.79	1,029.79	29.27**
Pressure	1	.04	.04	.00
Position	1	481.51	481.51	13.68**
Motion	1	53.22	53.22	1.51
Threat x Team	3	706.92	235.64	6.70**
Threat x Pressure	3	585.90	195.30	5.55**
Threat x Position	3	313.56	104.52	2.97
Threat x Motion	3	588.90	196.30	5.58**
Team x Pressure	1	27.51	27.51	.78
Team x Position	1	314.19	314.19	8.93**
Team x Motion	1	14.49	14.49	.41
Pressure x Position	1	185.62	185.62	5.28*
Pressure x Motion	1	288.42	288.42	8.20**
Position x Motion	1	24.73	24.73	.70
[a]Threat′ x Pressure x Position	1	1,338.13	1,338.13	
Error	5	175.94	35.19	
	31	6,621.66		

[a]Only 1 degree of freedom of the threat variable, Threat′, is present in this interaction.

analysis because the arbitrary manner in which the pseudofactors for threat were formed (threat′ is a pseudofactor) makes any physical interpretation of this interaction suspect.

The information contained in Table 5 requires interpretation. First addressed are the main effects, i.e., the influence of the five design factors on the response. The table lists team and position as being significant at the α=.05 level and threat at the α=.10 level. It is appropriate to note here that these main effects each have an alias, an effect which cannot be distinguished from the main effect because of its functional dependence on the main effect—a consequence of fractional factorial designs. For example, position is aliased with a four-factor interaction involving threat, team, pressure, and motion. In fact, all the main effects in this design are aliased with four-factor interactions. What allows us to interpret them as main effects and not interactions is the very reasonable assumption that the effects of a four-factor interaction can be ignored. Such a stance is loosely analogous to being willing to drop off the fourth-order terms in a Taylor series approximation. The statistical significance of these three main effects suggests that the miles traveled after degradation will likely change depending on which levels of the significant factors are tested. The nature of these changes is illustrated by the following.

Figures 4–8 give confirmation of the tabled significances and lend insight to the nature of the design factor's effect on the response. Each figure gives a histogram of values for each level of the main effect shown. Below each histogram, summary statistics are given—for example, the sample mean and standard deviation of the sample mean (S.E.M.). If a significant effect is present, at least one histogram should differ from the others with respect to its center, taken as the sample mean. (The sample mean is denoted by M when it coincides with a data point and N when it does not.) In Figure 4, the histogram corresponding to the 7.62-mm round with sidewall shots fired at a 45° angle to the direction of the tire tends to support greater distances traveled, notably the 84.9 mi of test number 28. A Newman-Keuls range test (Hicks 1982) indicated that the only claim for significant difference among levels could be made between the 10-g fragment and the 7.62-mm round at 45° with means of 33 mi and 43 mi, respectively. If observation 28 were discounted, no significant difference would be the result. The interpretation of Figures 5–8 is straightforward. Note that in Figure 5, Team 1 tends to travel farther than Team 2, and in Figure 7 steering tires tend to last longer than drive tires. More about each of these two effects follows.

Further interpretation of Table 5 leads one to consider the two-way interactions, several of which are statistically significant. As with the main effects, each of the two-factor interactions have higher-order-interaction aliases, in this case, three-way interactions. This makes interpretation problematic because there is not as great a distinction between two and three-way interactions as is between main effects and four-way interactions. In other words, we are not as sure that the influence seen is caused by the effect and not its alias. A table of effects and their aliases, in simplified form, is included in Appendix B. (Also in Appendix B, we discuss fixed vs. random effects.) We leave interpretation of these significant effects to those with a greater understanding of the tire-failure mechanism but advise caution because of the sparcity of observations for certain factor combinations and because of the alias problem noted above. However, we will discuss, as an example one, the team-by-position interaction, for which a plausible explanation is possible.

An interaction between two factors is said to be present when the influence of one factor on the response changes in the presence of different levels of the other factor. In Figure 9, examine the team-by-position interaction. Consider the influence of tire position on the

```
              3 gm                       10 gm                      7.62 mm / 45 deg           7.62 mm / 90 deg
MIDPOINTS.....................+.........................+.........................+....................
   90.000)
   85.000)                                                  *
   80.000)
   75.000)
   70.000)
   65.000)                                                                            *
   60.000)
   55.000)                     *                            *                         *
   50.000)*                                                 *
   45.000)*                                                 M
   40.000)                     *
   35.000)M*                   M**                          ***                       M
   30.000)**                                                *                         ***
   25.000)*                    *                            *                         *
   20.000)*                    **                                                     *

MEAN           34.125                   32.888                    43.063                    36.638
STD.DEV.       10.104                   11.860                    19.773                    15.548
S. E. M.        3.572                    4.193                     6.991                     5.497
MAXIMUM        50.400                   54.900                    84.900                    65.900
MINIMUM        20.400                   18.600                    24.900                    20.400
CASES INCL.         8                        8                         8                         8
```

Figure 4. <u>Main Effect, Threat.</u>

```
              team 1                                        team 2
MIDPOINTS.........................................+................
   90.000)
   85.000)*
   80.000)
   75.000)
   70.000)
   65.000)*
   60.000)
   55.000)*                                        **
   50.000)**
   45.000)*
   40.000)M
   35.000)*****                                    ****
   30.000)***                                      M**
   25.000)                                         ****
   20.000)*                                        ***

MEAN           42.350                                  31.006
STD.DEV.       16.098                                  10.661
S. E. M.        4.024                                   2.665
MAXIMUM        84.900                                  54.900
MINIMUM        20.400                                  18.600
CASES INCL.        16                                      16
```

Figure 5. Main Effect, Team.

```
              22 psi                                        30 psi
MIDPOINTS.........................................+.................
   90.000)
   85.000)                                         *
   80.000)
   75.000)
   70.000)
   65.000)*
   60.000)
   55.000)**                                       *
   50.000)*                                        *
   45.000)*
   40.000)*
   35.000)M****                                    M***
   30.000)                                         ******
   25.000)*                                        ***
   20.000)****

MEAN           36.713                                  36.644
STD.DEV.       14.445                                  15.257
S. E. M.        3.611                                   3.814
MAXIMUM        65.900                                  84.900
MINIMUM        18.600                                  24.900
CASES INCL.        16                                      16
```

Figure 6. Main Effect, Pressure.

```
           static                                         dynamic
MIDPOINTS.........................................+.............
  90.000)
  85.000)                                         *
  80.000)
  75.000)
  70.000)
  65.000)                                         *
  60.000)
  55.000)**                                       *
  50.000)*                                        *
  45.000)*
  40.000)*                                        N
  35.000)M**                                      ******
  30.000)****                                     **
  25.000)***                                      *
  20.000)*                                        ***

MEAN            35.388                               37.969
STD.DEV.        11.081                               17.751
S. E. M.         2.770                                4.438
MAXIMUM         54.900                               84.900
MINIMUM         18.600                               20.400
CASES INCL.         16                                   16
```

Figure 7. Main Effect, Position.

```
           drive                                          steering
MIDPOINTS.........................................+.............
  90.000)
  85.000)                                         *
  80.000)
  75.000)
  70.000)
  65.000)                                         *
  60.000)
  55.000)*                                        **
  50.000)*                                        *
  45.000)*
  40.000)                                         M
  35.000)M****                                    ****
  30.000)****                                     **
  25.000)                                         ****
  20.000)****

MEAN            32.800                               40.556
STD.DEV.        10.563                               17.256
S. E. M.         2.641                                4.314
MAXIMUM         54.900                               84.900
MINIMUM         18.600                               24.900
CASES INCL.         16                                   16
```

Figure 8. Main Effect, Motion.

```
                team 1                 team 1                 team 2                 team 2
                drive                  steering               drive                  steering
MIDPOINTS.....................+.....................+.....................+.................
  90.000)
  85.000)                      *
  80.000)
  75.000)
  70.000)
  65.000)                      *
  60.000)
  55.000)                      *                      *                      *
  50.000)*                     M
  45.000)*
  40.000)                      *
  35.000)M**                   **                     **                     **
  30.000)**                    *                      M*                     M
  25.000)                                                                    ****
  20.000)*                                            ***

MEAN          35.337               49.363                 30.263                 31.750
STD.DEV.       9.396               18.831                 11.666                 10.304
S. E. M.       3.322                6.658                  4.125                  3.643
MAXIMUM       50.400               84.900                 54.900                 54.900
MINIMUM       20.400               31.300                 18.600                 24.900
CASES INCL.        8                    8                      8                      8
```

Figure 9. Team x Position Interaction.

response. At the Team 1 level of the team factor, there is an apparent difference between the drive and steering positions. At the Team 2 level, there is no difference. Hence, the influence of position has changed according to team. In this instance, there is a possible explanation. Accept that severe vibration caused by irregularities in the run-flat device was extremely important in alerting teams to tire system failure. Accept further that such vibration in a steering tire makes it difficult to control the vehicle. Our conjecture is simply that the physically stronger Team 1 was willing to fight the vehicle for control longer than Team 2—hence, the significant interaction.

Four runs were conducted with both the drive and steering tires degraded: runs 10, 15, 20, and 29. The mean of the four runs was 27.05 mi, and the standard deviation was 5.53 mi. These runs were compared to the 16 runs in which the drive tire was damaged, this being the worst case level of the position factor. Those 16 runs had a mean of 32.8 mi with a standard deviation of 10.6 mi. In the strictest terms, no conclusive statistical test based on means is possible because assumptions are violated; however, Welch's t'-test (Hicks 1982), in our judgment the closest to being valid, finds no significant difference between the two-tire-damaged and drive-tire-damaged cases. The unfortunate misconception which led to no perfectly valid statistical test was the original thinking that the steering tires would be exposed to more stresses and would fail more quickly. The design incorporated the four two-tire-damaged runs with this in mind in preparation for a paired t-test analysis, where the pairings would be based on similar treatment combinations of steering tire failures. However, NATC loaded the vehicle with more of the load to the rear and this, or the position-by-team interaction, caused the more rapid failure of the drive tires. The final decision was that there was insufficient evidence to claim any difference between the two-tire-damaged and drive-tire-damaged configuration.

4. BLUEPRINT FOR STAGE 2

4.1 Purposes. The purposes of the Stage 2 test are to compare the relative performance of the STS candidates, including the standard, and to continue study of Stage 1 test conditions warranting further examination. The purpose of this section is to provide a blueprint for a test strategy to accomplish the tasks of Stage 2. A decision regarding which candidates to carry forward to the durability phase will be one result from this test.

Consequently, testing must be geared to source selection, not screening, requiring more samples to be allocated so that replications of test conditions are possible. This approach will provide for a better estimate of error variance under the model assumed, thus adding validity to the decisions made.

4.2 Design Factors. In this section the rationale is presented for each of the test conditions comprising the Stage 2 design. Threat is the first factor discussed. In Section 3.2, threat was found significant at the α=.10 level, but save for one point, observation 28, no reasonable significance claim could be made. Still, the sample means for each level of threat involving 7.62-mm rounds were nominally greater than those involving fragments. In Stage 2, this factor will be explored further with only two levels, one representing fragment damage and one representing 7.62-mm damage. The 10-g fragment was selected because it corresponded to the 152-mm threat munition. This munition was judged by the BRL Foreign Intelligence Office to be of greater interest than the 122-mm round. The 7.62-mm round with the 90° orientation to the sidewall was chosen because it is required according to the NATO/FINABEL standard.

Tire pressure will be fixed at 30 psi. The analysis of Stage 1 indicated that this factor had no effect, so only normal inflation will be used in Stage 2.

Tires under load will be damaged at rest and in motion. Although the motion factor was not found significant in Stage 1, the STS candidates are sufficiently varied in construction to warrant further examination of this factor in Stage 2.

The position of the degraded tire will be limited to the drive (right rear) position only. In Stage 1, the drive tires failed more quickly than the steering tires and thus represent a worst-possible-case scenario. Drive tires more closely approximated the two-tire-damaged case and showed similar performance under Team 1 and Team 2. Finally, several delays occurred in Stage 1 when degraded steering tires damaged special instrumentation mounted under the front of the vehicle. Those specific delays can be avoided by degrading only drive tires.

The team factor significantly influenced the response in Stage 1. It must be included in Stage 2 because failing to recognize its influence could bias the analysis. Team 1 and

Team 2 personnel used in Stage 1 will be used again in Stage 2. Recall that team showed the greatest difference when testing steering tires. By focusing on drive tires in Stage 2, the team effect should be greatly reduced.

Five manufacturers will offer prototypes for Stage 2. The experiment design will be structured for only five levels of manufacturer. Some testing of the standard STS will be mixed in among the design runs to verify consistency with the Stage 1 baseline test.

4.3 Experiment Design. The experiment design for Stage 2 is largely determined by the design factors chosen. In review, threat, motion, and team will be considered at two levels with five levels corresponding to manufacturers. A 5 x 2^3 full factorial design, allowing for some replication, is appropriate.

5. CONCLUSION

The Stage 1 test was conducted as outlined in BRL-TR-3111, and an appropriate statistical analysis was performed. The analysis showed threat, team, and position to be significant factors in determining the response, miles until failure after degradation, for the standard HMMWV STS. Pressure and motion were insignificant. An outline for Stage 2 was developed based on the analysis of Stage 1. By performing the Stage 1 test prior to testing the manufacturer's prototypes, a baseline of performance for the standard STS was empirically established, important experimental conditions were controlled, and test conditions of interest in Stage 2 were reduced from 64 to 8.

Finally, BRL established and implemented an acceptable means for simulating fragment damage to tire systems. A test stand capable of supporting the degradation of tires in motion and under load was piloted by the BRL. The test design was created and the analysis was performed by BRL personnel. BRL assumed responsibility for the general test conduct, delegating on-site control to the Test Director at NATC.

6. REFERENCES

Bodt, B., J. Schall, and S. Snapp. "Survivable Tire System (STS) Test Strategy: Technical Phase." BRL-TR-3111, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1990.

Cochran, W., and G. Cox. Experimental Design. New York: John Wiley and Sons, 1957.

Dreiling, J., S. Pietzyk, and H. Schrag. "Survivable Tire Test." CDEC-TR-87-014, Combat Developments Experimentation Center, Fort Ord, CA, 1987.

Graybill, F. Theory and Application of the Linear Model. Boston: Duxbury Press, 1976.

Green, E., M. Gray, R. Johnson, and R. Multer. "Survivable Tire Test Results." Technical Report GL-87-21, Waterways Experiment Station, Corp. of Engineerings, Vicksburg, MS, 1987.

Hicks, C. Fundamental Concepts in the Design of Experiments. New York: Holt, Rinehart and Winston, 1982.

Kempthorne, O. The Design and Analysis of Experiments. New York: John Wiley and Sons, 1952.

NATO/FINABEL Standard, 1984.

INTENTIONALLY LEFT BLANK.

APPENDIX A:

SUBJECTIVE ASSESSMENTS OF RIDE QUALITY

Subjective assessments of ride quality were gathered via questionnaire from participating drivers after each lap. This information will be used as a baseline on ride quality against which to compare the new STS technologies in Stage 2. No inference beyond that is intended. Ride quality categories include traction, stability, vibration, steering, and control. For each category, the driving team rated the ride as being very good, good, above average, below average, poor, or very poor.

Data were first summarized by choosing only one rating for overall ride quality on each test run; in other words, one rating pooled over drivers within a team and over all ride quality categories. This was done to simplify the analysis and to avoid redundancy. Drivers within teams responded similarly in all cases, and if one ride aspect was poor or good, all ride aspects tended to be so.

In the profile runs, both teams rated the standard system highly. All runs with tires inflated to 30 psi were rated good. Runs involving 22 psi inflation were rated as very good by Team 2 and as good or above average by Team 1.

Rating frequencies for the screening test runs are given in Table A-1. The frequencies are broken out according to the levels of each of the screening test factors—32 ratings total for each. Of interest are situations where the ride quality rating is seemingly influenced by a factor. The table suggests that the teams respond differently, Team 2 being more optimistic about ride quality than Team 1. No other obvious influence is present.

Table A-1. Frequency Table for Subjective Ratings of Ride Quality

	Subjective Rating					
Factor Levels	Very Good	Good	Above Average	Below Average	Poor	Very Poor
3 g		3	2	3		
10 g		4	1	3		
7.62 mm/45°		4		4		
7.62 mm/90°	1	2	2	2	1	
Team 1			4	11	1	
Team 2	1	13	1	1		
22 psi		6	4	5	1	
30 psi	1	7	1	7		
drive	1	5	1	8	1	
steering		8	4	4		
static	1	7	2	5	1	
dynamic		6	3	7		

INTENTIONALLY LEFT BLANK.

APPENDIX B:

TWO STATISTICAL NOTES

1. EFFECTS AND ALIASES

Section 3.2 uses the term "alias" to describe an effect indistinguishable from the one under study. Further, it suggests that knowledge of the relationship between effects and their aliases is required to fully interpret the analysis of variance appearing as Table 5. In Table B-1 below, those relationships are given in simplified form. The nature of the simplification is to ignore the fact that only partial information (not all degrees of freedom are used) is available for certain terms. The terms are listed without reference to the degrees-of-freedom consideration. The table can be used to recognize general relationships between factors and their aliases, expressed in the notation of the original design factors under study.

2. FIXED vs. RANDOM EFFECTS

All experiment factors are treated as fixed effects in the statistical analysis. The reader will no doubt agree that this is the proper stance for threat, position, pressure, and motion but will initially disagree with this posture regarding team. The obvious motivation for calling team a fixed effect is that the fractional factorial design defies analysis otherwise, but this alone is insufficient cause for straying from the traditional view that operator-related effects are random, not fixed. The notion that operator effects are random is nothing more than a model choice that suggests the levels (operators selected) of the design factor are realizations of a random sample conducted on some population of potential operators. For a complete description, see Graybill (1976). In practice such a random sample is rarely, if ever, performed, but pretending that it has been (i.e., loosely analogous to accepting that the operators chosen are representative of the population) gives the experimenter the license to generalize the inferences based on the sample to the population of operators if it is necessary to do so. In this experiment, it is not necessary to do so; the secondary role of the team effect is clearly noted in Sections 2.2 and 4.2. Further, civilian driving teams assembled by NATC have not been shown to be representative of Army drivers. Inferences involving team are thus restricted to the driving teams studied.

Table B-1. Effects and Aliases

Effects	Aliases
Threat	Team x Pressure x Position x Motion
Team	Threat x Pressure x Position x Motion
Pressure	Threat x Team x Position x Motion
Position	Threat x Team x Pressure x Motion
Motion	Threat x Team x Pressure x Position
Threat x Team	Pressure x Position x Motion
Threat x Pressure	Team x Position x Motion
Threat x Position	Team x Pressure x Motion
Threat x Motion	Team x Pressure x Position
Team x Pressure	Threat x Position x Motion
Team x Position	Threat x Pressure x Motion
Team x Motion	Threat x Pressure x Position
Pressure x Position	Threat x Team x Motion
Pressure x Motion	Threat x Team x Position
Position x Motion	Threat x Team x Pressure

INTENTIONALLY LEFT BLANK

No of Copies	Organization
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	HQDA (SARD-TR) WASH DC 20310-0001
1	Commander U.S. Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander U.S. Army Laboratory Command ATTN: AMSLC-DL 2800 Powder Mill Road Adelphi, MD 20783-1145
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-IMI-I Picatinny Arsenal, NJ 07806-5000
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
1	Commander U.S. Army Armament, Munitions and Chemical Command ATTN: SMCAR-ESP-L Rock Island, IL 61299-5000
1	Director U.S. Army Aviation Research and Technology Activity ATTN: SAVRT-R (Library) M/S 219-3 Ames Research Center Moffett Field, CA 94035-1000

No of Copies	Organization
1	Commander U.S. Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander U.S. Army Tank-Automotive Command ATTN: ASQNC-TAC-DIT (Technical Information Center) Warren, MI 48397-5000
1	Director U.S. Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
(Class. only)1	Commandant U.S. Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
(Unclass. only)1	Commandant U.S. Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905-5660
1	Air Force Armament Laboratory ATTN: AFATL/DLODL Eglin AFB, FL 32542-5000
	Aberdeen Proving Ground
2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Cdr, USATECOM ATTN: AMSTE-TD
3	Cdr, CRDEC, AMCCOM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-MSI
1	Dir, VLAMO ATTN: AMSLC-VL-D
10	Dir, BRL ATTN: SLCBR-DD-T

No. of Copies	Organization
1	Commander US Army Materiel Command ATTN: AMCAE, C. Chapin 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Director Survability Management Office ATTN: SLCSM-D Adelphi, MD 20783-1145
1	Director VLAMO ATTN: SLCVA-D Adelphi, MD 20783-1145
2	Commander US Army Tank-Automotive Command ATTN: AMSTA-RTS, A. Pacis (2 cys) Warren, MI 48397-5000
	Aberdeen Proving Ground
1	Cdr, USACSTA ATTN: STECS-DA-PA, V. Visnaw
1	Dir, USAMSAA ATTN: AMXSY-CSD, K. Unruh

USER EVALUATION SHEET/CHANGE OF ADDRESS

This laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers below will aid us in our efforts.

1. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______

2. How, specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______

3. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______

4. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______

BRL Report Number BRL-TR-3226 Division Symbol ______

Check here if desire to be removed from distribution list. ____

Check here for address change. ____

Current address: Organization ______
Address ______

DEPARTMENT OF THE ARMY
Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

OFFICIAL BUSINESS

BUSINESS REPLY MAIL
FIRST CLASS PERMIT No 0001, APG, MD

Postage will be paid by addressee.

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066